

RADIATION HAZARD IN SPACE

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(NASA-TT-F-15400) RADIATION HAZARD IN
SPACE (Scientific Translation Service)

N74-19724

22 p HC \$4.25

CSCL 06R

Unclas

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G3/04 32709

Translation of: "Radiatsionnaya
opasnost' v kosmose", Priroda, No. 10,
October, 1973, pp. 10-16



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

APRIL 1974

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L. I. Miroshnichenko *

How great is the radiation hazard for man in space? How /10**
does it depend on the level of solar activity, flight duration
and other factors? Astro-physicists and engineers, physicians
and biologists are busy with this complex and multifaceted problem.
The recent investigations of American scientists have led to an
unexpected result: the safest periods for long-term spaceflights
are not those near the minimum of solar activity, as was thought
earlier, but those near the maximum. However, this paradoxical
conclusion requires confirmation. The fact of the matter is that
it is not solar activity alone that exerts a decisive influence on
the propagation of cosmic rays of both galactic and solar origin.
Here, a significant role belongs to dynamic changes in the
physical conditions in interplanetary space, whose study in
our day has come to the forefront. However, the problem of
predicting solar flares during this process remains a pressing one,
as before.

Sources of Radiation Hazard

Which particles create the greatest radiation hazard for
cosmonauts? These are primarily protons and electrons of the
Earth's radiation belts. Moreover, in outer space a significant
flux of galactic cosmic rays — protons, α -particles (helium nuclei)

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and heavier nuclei — is constantly present. Finally, from time to time interplanetary space is filled with solar cosmic rays — basically fast protons from solar flares. Their flux can exceed the radiation background created by galactic cosmic rays by thousands of times, while the energy density is from 1 - 10,000 times that of the galactic particles

Radiobiologist-specialists have no doubt that the radiation hazard in space resulting from all these sources, in the absence of special protective measures, is both real and significant. Therefore, to successfully accomplish a flight, a certain system of radiation security is necessary, a system which will enable one to decrease the dose of radiation to a regulated (permissible) level with an assigned degree of reliability. In order to attain the prescribed level of reliability (not less than 99%), one must obviously consider all sources of radiation of significance for the upcoming flight. These sources can be divided into two classes: those constantly active and those statistically active, i.e., those active through an undetermined interval of time. The first class includes radiation belts and galactic cosmic rays; the second — protons from solar flares.

Although the radiation belts are subject to temporary changes, their spatial structure remains stable and is basically constant. Galactic cosmic rays are a more dynamic source; however, it is relatively easy to take their temporal and spatial variations into account. Dose levels in the spacecraft from constant sources can in principle be calculated in advance with adequate accuracy. But the estimate of radiation hazard from the statistically acting sources — solar flares — can only have a probable character. In the meantime, the radiation hazard caused by solar flares becomes determinative in a number of cases. This immeasurably complicates the task, since the weight

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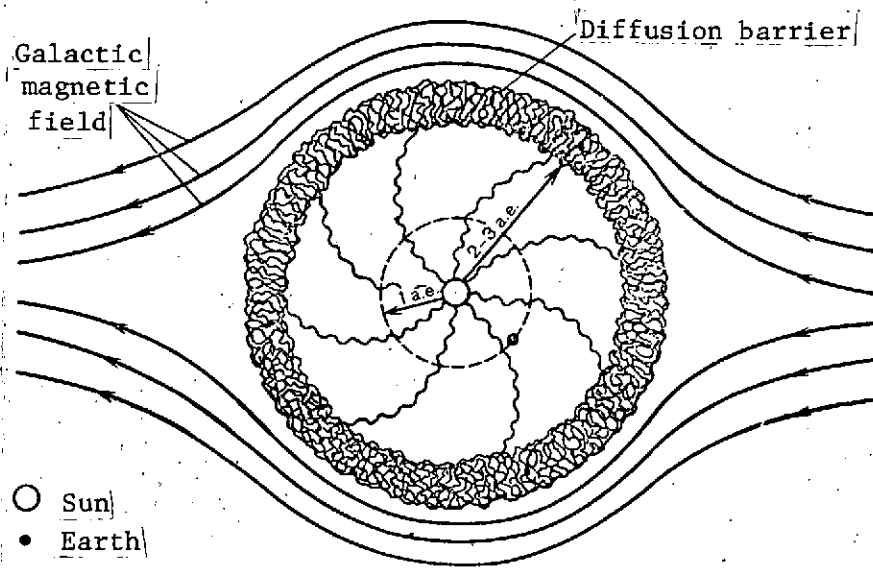


Figure 1. The region "blown out" in the solar system by the flux of solar wind. The magnetic fields "frozen" to the plasma of the solar wind (wavy lines) "throw" the galactic cosmic rays far beyond the limits of the Earth's orbit (indicated by the dashed line). The "blown out" region is surrounded by a diffusion barrier several tenths of an astronomical unit thick (after A. K. Lavrukhina). With a strengthening of the wind, i.e., with an increase in the activity of the sun, the dimensions of the region increase and the intensity of the cosmic rays correspondingly drops.

limitation of the spacecraft makes it impossible to have reliable protection ensuring cosmonaut safety during solar flares of different intensity.

Cosmic Rays and Solar Activity

The radiation hazard in outer space (beyond the limits of the magnetosphere) is to a significant degree determined by the dynamic processes in the interplanetary medium. A decisive role in these processes belongs to the solar wind — a continuous flux of plasma from the sun with the magnetic fields seemingly frozen to it [1].

The frozen magnetic fields, carried great distances from the Sun by the solar wind, act in a determinable fashion on the cosmic rays coming in from the Galaxy: the wind "blows out" a region in the solar system (Figure 1) in whose interior the intensity of cosmic rays is always lower (but never zero!) than the intensity outside it [2]. The "throwout" effect of the magnetic fields of the solar wind is stronger, the greater the power of the wind. Thence it is clear that with a strengthening of the wind the dimensions of the region increase. The power of the wind depends on the level of solar activity, which is usually characterized by the Wolf number W . Solar activity fluctuates with a period of about 11 years. The intensity of I galactic cosmic rays changes with the same period. The correlation between the values of W and I is inverse: with an increase in the Wolf number the intensity of cosmic rays falls (Figure 2); however, there is no exact mathematical relationship between W and I .

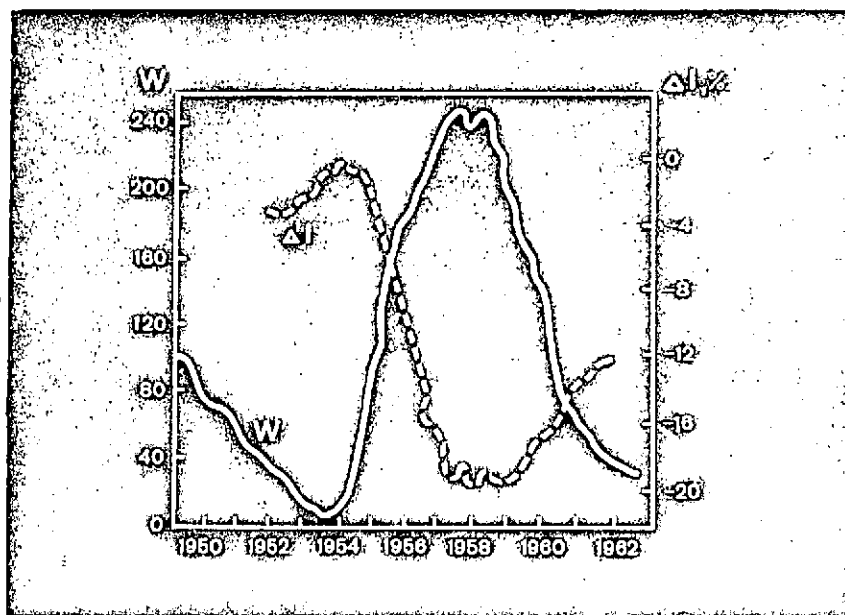


Figure 2. The 11-year variation in solar activity (Wolf number W) and change in intensity of cosmic rays ΔI (in percent of the maximum value of I). With an increase in the activity of the sun, the flux of cosmic rays decreases.



Figure 3. Tracks of heavy particles of cosmic rays on the inside of the helmets of the "Apollo" astronauts: on the left — the track of a particle which had passed through the helmet; right — circular track of a particle which entered the helmet through one side, went through it and stopped on the other side. Length of the tracks — 500 and 700 micrometers, respectively. With indirect illumination one can see the track shadows. (Photograph from the Magazine, "Science", Vol. 172, 1971, No. 3979.)

Based on these general concepts and taking into account the /12 results of recent experiments on spacecraft of the "Apollo" type, a group of American scientists (George Comstock, et al.) advanced the hypothesis that the main hazard for the health of astronauts is not posed by protons from solar flares, so much as by the heavy nuclei of galactic cosmic rays [3]. Here it is asserted that an increased flux of solar particles (in all cases, with the exception of the most powerful flares) can be stopped by the quite modest protection of the spacecraft. At the same time, the flux of strongly penetrating galactic particles in the period near the maximum of solar activity will be significantly reduced as the result of their "blow out" by the magnetic fields

of the solar wind. In the years of the activity minimum, the situation will be the opposite. Therefore, from the viewpoint of cosmonaut safety the beginning of the 1980's will be a much better period for a flight to Mars than the second half of this decade. What experimental facts serve as the basis for such conclusions?

Dosimetric Experiments on the "Apollo" Spacecraft

George Comstock, et al. investigated the tracks of cosmic rays in the plastic layers of the helmets of the astronauts who had participated in the circumnavigation of the Moon ("Apollo-8", 21-27 December, 1968) and in the landing on its surface ("Apollo-12", 14-24 November, 1969). In the interval between these flights, the level of solar activity evenly decreased. The scientists estimated the biological hazard for several types of irreplaceable cells. It proved that over the period of the "Apollo-12" flight from $3 \cdot 10^{-7}$ to $1.4 \cdot 10^{-4}$ parts of all cells (independent of their size) could perish.

In passing through dense matter, the heavy ionizing particle leaves a track which becomes visible during special processing (Figure 3). It is caused by excitation and ionization of atoms of matter during their simultaneous displacement, and during breakage of the bonds between them. It was established earlier that for certain types of cells the effect of heavy ions is lethal. With respect to the irreplaceable cells of man, however, such information is almost completely lacking. Inasmuch as this is extremely important for future long-term flights, the American scientists decided to use the helmets of the astronauts as unique detectors of the heavy particles of galactic cosmic rays.

The helmet casings were made of lexane — a plastic having a chemical composition such that only particles, with an ionizing capacity which exceeds the ionizing capacity

of a neon nucleus with an energy of about 7 Mev/nucleon, would leave tracks. At such a level of ionization, certain cells in the human kidneys lose their capacity to reproduce if the particle passes through the cell's nucleus. Hence, lexane can be considered a suitable material as a detector for estimating the dose of radiation from biologically hazardous particles.

The casings of five helmets were subjected to investigation. One of them belonged to G. Lovell (the commander of "Apollo-8") three were used by the "Apollo-12" astronauts, R. Gordon (spacecraft commander), A. Bean and C. Conrad; one more helmet served as the control. The latter was irradiated with cosmic particles during the ascent of a balloon into the stratosphere to an altitude of up to 41 km, with an atmospheric density above the balloon of 2.5 g/cm^3 (Fort Churchill, Canada, 11-12 July, 1970). The helmets were put through careful chemical processing with all precautions being taken. As measurements showed, the tracks detected belong to particles with a charge of $z \geq 10$, and most of them are nuclei of the iron group ($24 \leq z \leq 28$).

During the flight of "Apollo-8", the rate of track formation
 $(0.7[65 \cdot 10^{-7} \text{ cm}^{-2} \cdot \text{sec}^{-1} \text{ steradian}^{-1}])$ was approximately two times
less than that of "Apollo-12" and was three times less than that of the stratospheric experiment in 1970. Although Bean and Conrad spent 25 hours in the lunar module and about 8 hours directly on the surface of the Moon, the overall density of tracks in their helmets slightly exceeds the corresponding density in Gordon's helmet; Gordon spent the entire time in the spacecraft cabin. Two facts probably played a role here. First, the time spent by the two astronauts outside the spacecraft cabin (about 33 hours) comprised only about 14% of the total flight time (244.5 hours). Second, during the stay on the Moon or near it, half the flux of cosmic rays was absorbed by the Moon itself.

According to the assertion of G. Comstock, et al., the level of solar activity in the period of the "Apollo-8" flight was the same as during the stratospheric experiment of 1970. The difference between these periods in the rate of formation of tracks is attributed to the difference in screening materials — the covering of the spacecraft cabin and the layers of the atmosphere above the stratospheric balloon. The difference in the data of measurements for "Apollo-8" and "Apollo-12" reflects a genuine change in the flux of cosmic rays, the cause of which is the decrease in the level of solar activity in the interval between flights, and the corresponding increase in the flux of galactic cosmic rays.

This is confirmed by data in Climax (USA): the rate of counting secondary neutrons in December, 1968, was lower (3709) than in November, 1969 (3843), and approximately the same as in July, 1970 (3715). We checked the latter assertion, taking into account the fact that the effect of solar activity on cosmic rays begins to affect the Earth only several days after the appearance of a determinable spot (or group of spots) on the solar disk. This delay is inevitable, since the solar wind, which is propagated at a rate of 300-400 km/sec, requires no less than 4-5 days to cover the distance from the Sun to the Earth (150 million km). As it turned out, there is no full agreement between values of W and I in the periods under examination. On the average, however, the activity of the Sun several days prior to the flight of "Apollo-8" in December, 1968, was somewhat higher (and the intensity of cosmic rays in the period of the flight was correspondingly lower) than in November, 1969, during the flight of "Apollo-12", and approximately the same as in July, 1970 (Figure 4).

G. Comstock and his colleagues attempted to calculate the rate of formation of tracks for each of the three periods. These

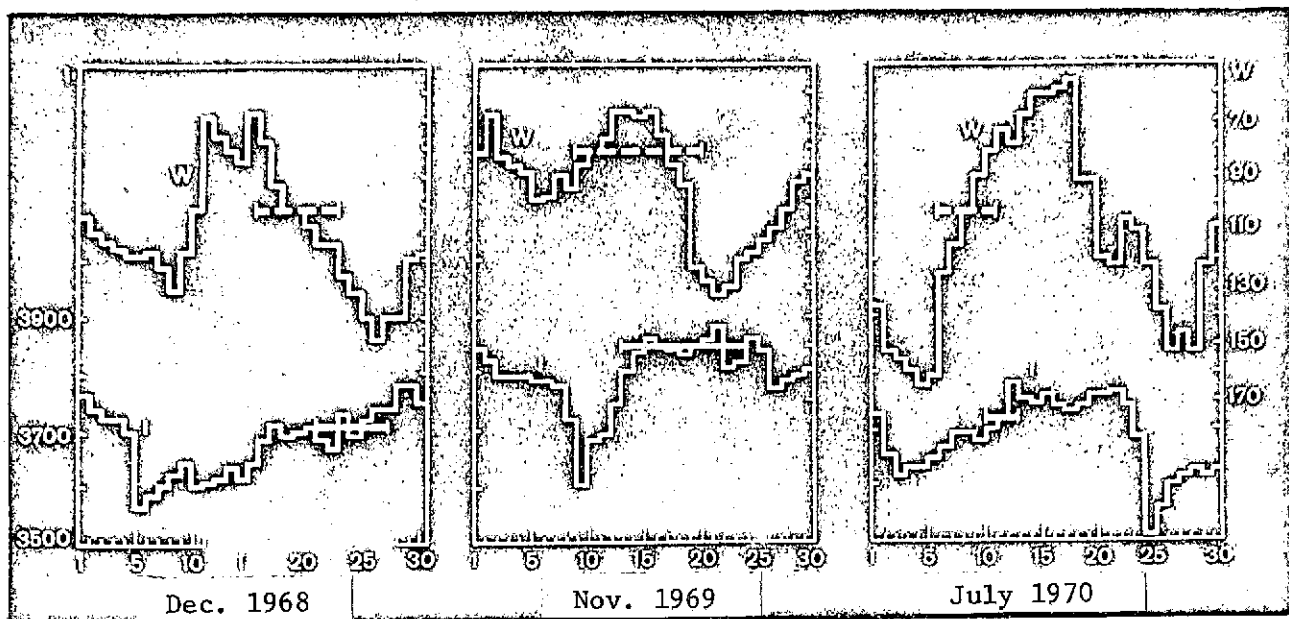


Figure 4. Solar activity — Wolf number W — and the intensity of cosmic rays I (in arbitrary units) during the flights of "Apollo-8" (1968), "Apollo-12" (1969), and the stratospheric experiment (1970). There is no complete agreement between the values of W and I; however, on the average solar activity several days prior to the flight (dashed line) in November, 1969, was lower, while the intensity of cosmic rays in the period of the flight was higher (solid line), than in December, 1968, and in July, 1970.

calculations are complex and entail a great amount of indeterminacy, since they were made for an idealized model of the spacecraft cabin with the inevitable simplified concepts concerning the flux and spectrum of the cosmic rays. However, the results of the calculations agree with the data of observations with an accuracy up to $\pm 30\%$.

The American scientists also estimated which portion of irreplaceable cells in the human organism would perish during a flight with a duration of about 2 years (to Mars and back). It was found that in the absence of special protection, cosmic rays could destroy a potentially important number of cells — about 12% of the cerebral cortex, 0.05% in the retina, and over 1.5% in

the central nervous system. The figures were obtained with the hypothesis that the flux of cosmic rays in the course of 2 years would be maintained at the same level as in the flight of "Apollo-12".

The "Radiation Sensitivity" of Man

The described experiments of the American scientists presently remain unique in at least two respects: first, the measurements were conducted in outer space over quite a long period of time; second, for the first time there was experimental confirmation of the relationship between the level of solar activity and the level of dangerous radiation in interplanetary space. This astrophysical aspect of the problem of radiation hazard is closely linked with another of its aspects — the radiobiological aspect. Although there are as yet many unsolved problems in radiobiology, its experimental achievements seem to us more impressive than the quite modest achievements in the field of predicting solar activity and the radiation situation in interplanetary space.

When estimating the radiation hazard of spaceflight it is necessary to take into account the working capacity of the cosmonaut during exposure to radiation and afterward, his capacity to carry out a complex combination of tasks relating to successfully accomplishing the flight program. The feelings and working capacity of the cosmonaut who has been exposed to radiation, in their turn, will depend on the condition of the separate "critical" systems of his organism.

At the base of the harmful effect of radiation (electromagnetic and corpuscular) lies the well studied process of ionization. Electromagnetic radiation causes a relatively uniform volumetric ionization. Its value decreases exponentially proportionate to the increase in thickness of the absorbent.

Heavy particles create a higher density of ionization along their path. At the end of the path length, with a decrease in the velocity of the particle to zero, its capacity for ionization sharply increases [4]. Dependent on particle energy, the ionization maximum will be reached at different depths. Therefore, the result of irradiation * will depend on several factors: the intensity of the particles and their energetic spectrum, the depth of location and the "radiosensitivity" of the particular organ.

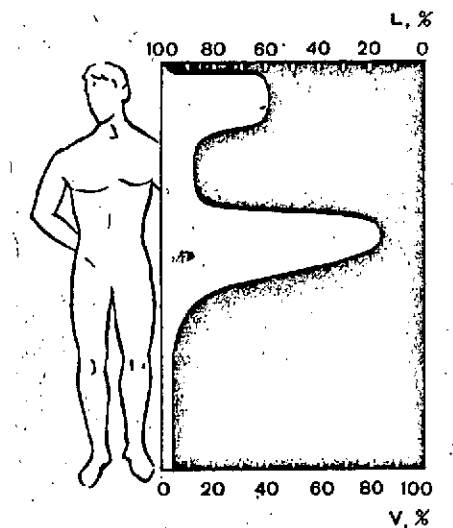


Figure 5. Distribution of radio damage along the axis of the human body:

V- probability of survival thanks to screening of certain regions of the body during irradiation with a minimum lethal dose;
L- probability of lethal result with the same conditions of irradiation.

Greatest interest in this regard attaches to the bone marrow and tissue of the gastrointestinal tract. According to the data of a group of Soviet scientists (V. S. Morozov, et al.), in the first case the effective depth is 5 cm, and in the second—15 cm. For example, if a beam of protons strikes the surface of the body in the region of the bone marrow, and these protons have an energy of 120 Mev, at a depth of 5 cm the harmful effect will be greater than in the surface layers.

* Translator's note: Illegible in foreign text.

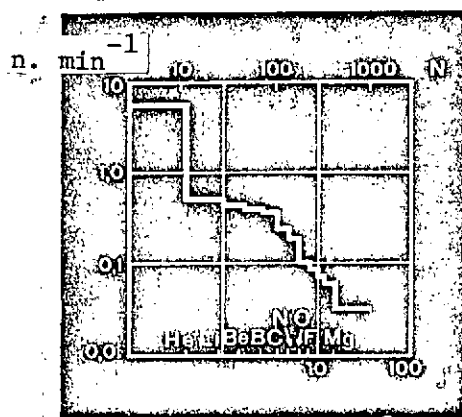


Figure 6. Frequency of Cerenkov flashes induced in the vitreous body of the eye by cosmic ray nuclei with various charges (indicated by the chemical symbols). Along the axis of the abscissa: bottom — relative intensity of j light; top — number N of Cerenkov photons; along the axis of the ordinate — number n of observed flashes per minute.

This pertains only to protons of such energy that when passing through the tissue they can yield a peak of ionization. For higher energy protons the distribution of absorbed doses through the tissues is more even and damage primarily occurs in the gastro-intestinal tract and bone marrow. For very low energy protons, damage to the skin, eyes and germ cells begins to play a certain role.

The relative importance of damage to any particular organ is illustrated in Figure 5, where a somewhat idealized distribution of radiosensitivity along the axis of the human body is shown. In this drawing, taken from the work of the Soviet scientists, B. I. Davydov, et al., the probability of human survival when certain separate regions of the body are screened in the process of irradiation with a minimum lethal dose is shown [6]. If, for example, the stomach is screened, the probability of survival reaches almost 90%; if only the legs are screened, the probability of survival does not exceed 5%. Hence, the greatest accrual of the

overall harmful effect pertains to the gastrointestinal tract, then to the head, and to a lesser degree to the other organs and tissues. One should specifically bear these facts in mind when considering corpuscular radiation of the cosmic ray type, in which the energetic spectrum and charge distribution can sharply change / 15 in time and space.

Man's sensitivity to cosmic rays was recently confirmed by a new and quite unique method — by means of visually observing cosmic rays.

During the flights of the "Apollo-11", "Apollo-12", and "Apollo-13" spacecraft, the astronauts saw light flashes with a frequency of about 1 flash per minute [7]. These flashes were even observed when the astronauts' eyes were closed. The cause of the flashes was cosmic rays passing through the hull of the spacecraft and their reaction with the eyeball [8].

The possibility of this effect had been pointed out 17 years before the flight of "Apollo-11" by the American scientist K. Tobias. In studying the radiation hazard during spaceflights, he concluded that man, adapted to darkness, must "see" trajectories with strong ionization in the form of small flashes of light. Hence, the problem is not a new one; the observations of the astronauts have only increased the interest in it.

To verify his hypothesis, Tobias and his associates at the Lawrence Laboratory in Berkeley conducted an experiment with artificial cosmic rays — fast particles obtained in an accelerator. The proton synchrotron was used (a modified bevatron) which could accelerate nitrogen ions to an energy of 36 Gev. Three scientists — Nobel Prize winner, E. M. MacMillan, Astronaut F. Chapman and Prof. K. Tobias — having placed their heads in the flux of nitrogen ions, observed light flashes, but only in those

positions when the ion beam passed through the inner part of the retina. If the beam penetrated the occipital lobes of the brain (where the neural perception of imagery is formed), the anterior portion of the retina or the vitreous body, the flashes were not observed. Thus it was concluded that fast ions produce flashes only when they directly interact with the retina, and only then when they have reached the end of their path length, when ionization is maximum.

Even before this experiment, similar flashes were observed from neutrons. Experimentors in the U.S.A. and England placed their heads in a neutron beam and also saw "lightening": the neutrons generated protons which then affected the retina.

In space the energy of ions reaches greater magnitudes than it does in laboratory accelerators. Therefore, part of the flashes could be created by another mechanism — Cerenkov emission of fast ions in the vitreous body of the eye [9]. Figure 6 shows the frequency of Cerenkov flashes induced in the vitreous body of the eye by nuclei of cosmic rays with various charges C . The intensity of the flashes is proportional to the square of the particle's charge. Terrestrial observers cannot see much flashes, inasmuch as the heavy nuclei of primary cosmic rays — protons, α -particles, carbon nuclei, oxygen nuclei, iron nuclei and the nuclei of other elements — do not reach the Earth's surface due to absorption and decay in the atmosphere.

It is interesting that before the flight of "Apollo-11" the astronauts did not observe such flashes. In the meantime, the

orbits of "Gemini" type spacecraft also went above the atmosphere, where cosmic rays are not absorbed. The difference could be explained by two reasons. First, the Earth's magnetic field is strong enough to deflect part of the cosmic rays. Second, in these early flights the astronauts kept the cabin ports closed and constantly talked with the Earth. Under these conditions there were neither the periods of calm nor of adaptation to darkness vital for observing flashes.

The Radiation Hazard during Solar Flares

The spaceflight occurs under conditions when several stressors act on the astronaut either simultaneously or in varying sequence (g-forces, vibration, weightlessness, altered gaseous composition of the atmosphere in the spacecraft cabin, etc.). The unusual conditions of flight create certain difficulties in estimating permissible doses, inasmuch as the combination of stressors can significantly alter the radiobiological effect of irradiation. During this process combinations are possible in which the radio-vulnerability will increase, or, on the other hand, decrease. Without taking these characteristics into account, one cannot with sufficient accuracy establish norms of permissible radiation for cosmonauts, particularly during long-term flights.

The combined effect of spaceflight factors has as yet been inadequately studied. For this reason, at present, when estimating the permissible doses one must base one's findings on the most unfavorable conditions of irradiation. With this approach, the most dangerous source of radiation is solar flares. Their probability character requires strict regulation not only of dose, but also of the risk of their exceeding the permissible dose.

From the viewpoint of radiation hazard, short-term and long-term flights should be examined separately, since the character of

radiation effect in these flights differs. Three dose categories, measured in BER's (biological equivalent of radiation), are recommended today for short-term flights: permissible dose-15 BER, justifiable risk-50 BER and critical dose-125 BER [10].

During long-term spaceflights the radiation hazard increases. The basic contribution to total dose will be made by chronic irradiation resulting from galactic cosmic rays (50-100 BER/year). Repeated acute exposures during solar flares are also possible (5-50 BER per flare), whose probability of appearance increases with the increase in flight duration. For example, during a /16 flight lasting 200 days the probability of 6 flares of the 12 November 1960 type (a flare with a moderate particle flux) is 16%, while that of 2 flares of the 23 February 1956 type (a flare with the greatest flux of high-energy particles recorded up to now) is about 2%. In that case the sum dose can reach 80-100 BER even behind a screen 20 g/cm² thick.

The calculations of Soviet scientists, O. D. Brill, Ye. Ye. Kovalev, et al., [11], show that the doses from solar flares can reach tens and hundreds of BER behind a screen of several grams per cm². For example, behind a screen with a thickness of 2 g/cm² the dose from emissions of solar flares is from 800 to 1500 BER/year, and behind a screen with a thickness of 25 g/cm² it is from 60 to 500 BER/year. These figures are quite vivid enough to imagine the difficulties of providing for the radiation safety of cosmonauts. Together with this, the great difference between the maximum and minimum values of the calculated doses once again points us toward the problem of predicting the solar flares and the conditions of particle propagation in interplanetary space. A detailed analysis of this difficult problem would lead us too far afield. Therefore, we shall limit ourselves here to a few notes.

Observations have established that flares of solar protons with an energy greater than 500 Mev, observed on the Earth, occur in periods of increase or decrease in solar activity, but not at the moments of its maxima (Figure 7). As a rule, such flares are accompanied by intensive fluxes of particles with energies of ~10-100 Mev. This fact, which has not yet been given any single explanation, is doubtlessly very important for planning long-term flights.

In the absence of flares, the radiation situation near the Earth and in the Solar System as a whole (to a distance of about 2-5 astronomical units) is formed over the course of a long period of time — at least over the period of an entire solar revolution (about 27 days). Therefore, a long-term forecast of the radiation hazard from galactic cosmic rays must be based on modern concepts of the dynamics of solar activity and the interplanetary medium. In this regard, the experimental results obtained aboard the "Apollo" spacecraft by a group of American scientists are very important. However, their conclusions concerning the role of heavy nuclei * narrow the problem considerably, and their assertion of the slight role of solar cosmic rays, obviously does not stand up to criticism.

The radiation barrier undoubtedly is a serious obstacle for making long-term spaceflights. Together with this, the successful flights of Soviet and American astronauts, with durations of up to several weeks, have shown that man in space does not find himself absolutely defenseless against dangerous radiation. There are methods and facilities at the disposal of the cosmonaut which enable him to protect himself against the

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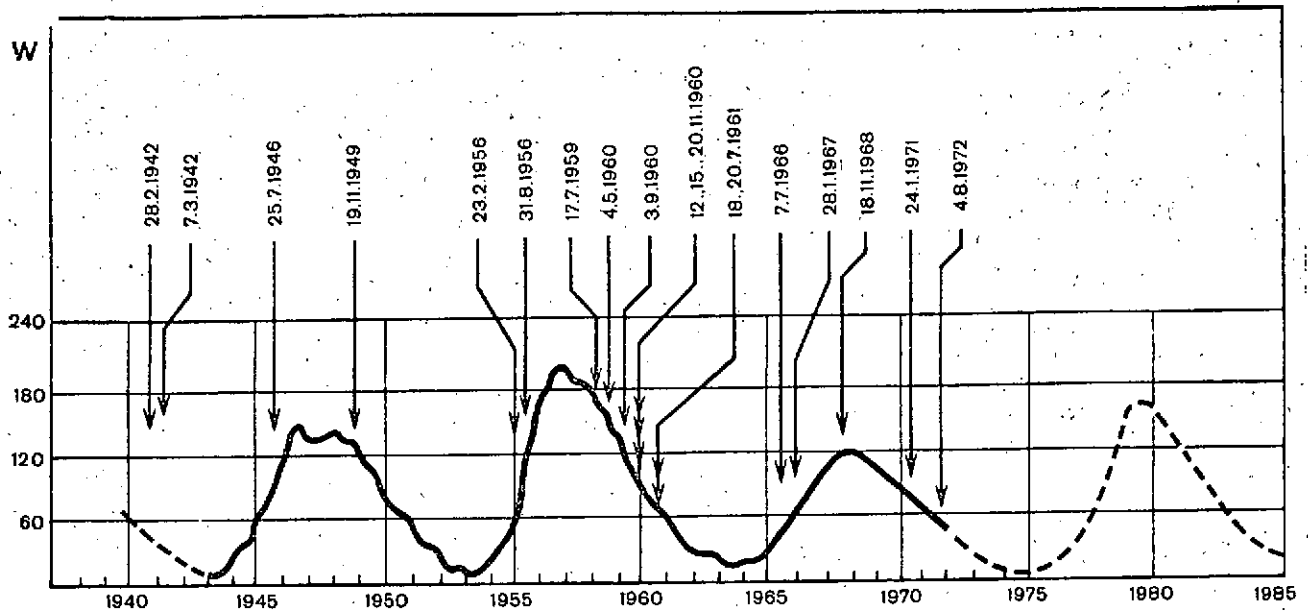


Figure 7. Variations in the frequency of flares of solar cosmic rays observed on the surface of the Earth, dependent on the level of solar activity expressed in Wolf numbers W. All flares recorded over the past 30 years (1942-1972) occurred in periods of increase or decrease in solar activity, but not at moments of its maxima.

effect of cosmic radiation and to decrease its harmful effect. And although this problem is not entirely solved as yet, the efforts of engineers and scientists in recent years have achieved hopeful results in this field.

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Translated for National Aeronautics and Space Administration
under contract No. NASw 2483, by SCITRAN, P. O. Box 5456, Santa
Barbara, California, 93108.

1. Report No. NASA TT F-15,400	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle RADIATION HAZARD IN SPACE		5. Report Date April 1974	
		6. Performing Organization Code	
7. Author(s) L. I. Miroshnichenko		8. Performing Organization Report No.	
		10. Work Unit No.	
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASw-2483	
		13. Type of Report and Period Covered Translation	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code	
15. Supplementary Notes Translation of: "Radiatsionnaya opasnost' v kosmose", Priroda, No. 10, October, 1973, pp. 10-16.			
16. Abstract A discussion of the radiation hazard in space travel as it has been estimated based on the data of Soviet and American spaceflights and terrestrial experiments. Calculations, charts and graphs are provided to clarify the text. It is stated that while a significant problem exists with respect to long-term flights, science and engineering will find a way to solve it. Many data are drawn from the Apollo projects.			
17. Key Words (Selected by Author(s))		18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price